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EFFECTS OF ANGULAR VARIATION ON SPLIT D DIFFERENTIAL EDDY CURRENT PROBE RESPONSE (POSTPRINT)

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The complexity of the models used in validation studies over the last few years has increased. Complexity has been included in the probe operation, the core/coil shape, the inclusion of ferrite cores, and the inclusion of dimension and orientation variation. An issue with these validation studies is there is no quantitative understanding of how a small change in a parameter affects the probe response. This study will look at the variation of probe response over a range of variations in multiple orientations. In addition, a sensitivity study will be performed to determine which orientations produce the greatest variations in response and if there are parameter levels where the response is more affected by the variation.

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Effects of Angular Variation on Split D Differential Eddy Current Probe Response

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Abstract. The complexity of the models used in validation studies over the last few years has increased. Complexity has been included in the probe operation, the core/coil shape, the inclusion of ferrite cores, and the inclusion of dimension and orientation variation. An issue with these validation studies is there is no quantitative understanding of how a small change in a parameter affects the probe response. This study will look at the variation of probe response over a range of variations in multiple orientations. In addition, a sensitivity study will be performed to determine which orientations produce the greatest variations in response and if there are parameter levels where the response is more affected by the variation.

INTRODUCTION

Model validation studies [1-8] over the last few years have seen increased levels of complexity added to push the state-of-the-art modeling software used in eddy current NDE today. The added complexity has allowed for the creation and validation of more realistic probe models. However, this is only the first milestone toward much larger goals. With increasing use of inversion algorithms for sizing of flaw indications, there is a need to improve the characterization of the probe models and inputs that go into these algorithms. The asymmetries and orientation variations included in previous validation studies [7-8] must be included in inversion routines to get the most accurate results for the desired inverted flaw size parameters. However incorporating these variations in a conventional sense, running large numbers of models with slightly varied parameters, is too time consuming and computationally expensive. If the effect these variations have on probe response can be quantified, then they can be incorporated into the inversion routine directly. This should reduce the time and computational expense of addressing such variations. To incorporate all possible effects, a number of sensitivity studies must be performed to determine the response change with respect to various parameter variations. This paper will present a study of the effect of angular variations on probe response. The details of the model construction and implementation of the angular variation will be discussed. The model results and data analysis performed to determine the sensitivity will be presented in detail. In addition, conclusions about the nature of the simulations including any remaining challenges will be given.

PREVIOUS WORK

As mentioned above a number of previous validation studies have been performed in the past. All of these studies have provided input into this current effort in some form, but the contributions from two will be discussed in more

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detail in this section. The first was a study [6] performed using a commercial split D differential probe, but was novel in that actual impedance values were compared to the simulated code outputs. The majority of differential probe validation studies use commercially available eddy current meters for data comparison. These meters only give a voltage representation of the impedance change. By using the actual impedance values, the agreement can be truly quantified without having to perform additional processing on the data. Furthermore, this study created a framework for running and analyzing data from simulations where multiple parameters were altered. The second study [7] was a validation where dimension and orientation variations were incorporated into the models to determine how capable of accurately modeling asymmetries inherent in real world probes. This second study made use of the same novel connection system as the first enabling true impedance based comparison. These two studies provide a level of confidence that the modeling software can be used to represent conventional eddy current measurements where various parameters are changed. In addition, they show that even if there are variations in the coil dimensions and orientation, the results will still be accurate when compared to experimental impedance data.

PROBLEM DESCRIPTION

The problem being simulated is relatively simple; a split D differential probe is scanned over an electric discharge machined (EDM) notch in a titanium specimen. The probe is scanned in the direction and orientation shown in Figure 1. The direction was chosen based on the results of previous model validation studies [5-8]. Based on these past results the chosen direction provided the best agreement with various notch lengths. All scans were 241 points in length with a step size of 0.05 mm. The probe model is based on a commercially available split D differential probe with a center frequency of 4 MHz that is well balanced. The notch used for all simulations was representative of a notch in a Ti EDM standard. The notch is nominally 1.524 mm long with a 2/1 length/depth aspect ratio and 0.127 mm wide.

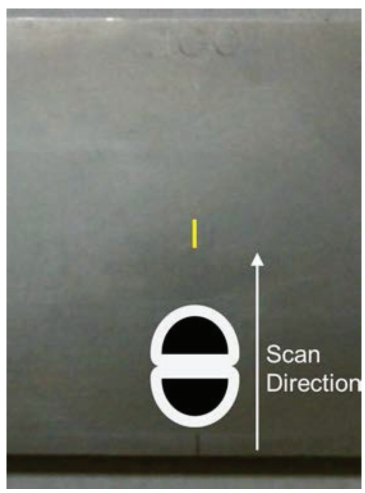


FIGURE 1. Problem setup showing the scan direction for all simulations

SIMULATION DETAILS

All simulations were run in VIC-3D® which is a volume integral code developed by Victor Technologies [9-10]. VIC-3D® begins with the steady state form of Maxwell's Equations given below (1, 2). In these, **E** is the Electric field intensity, **B** is the magnetic induction, **M** is the magnetization, and **J** is the true electric current density.

$$\nabla \times \boldsymbol{E} = -j\omega\boldsymbol{B} \tag{1}$$
$$\nabla \times \boldsymbol{B} = j\omega\mu_o\epsilon_o\boldsymbol{E} + \mu_o\nabla \times \boldsymbol{M} + \mu_o\boldsymbol{J} \tag{2}$$

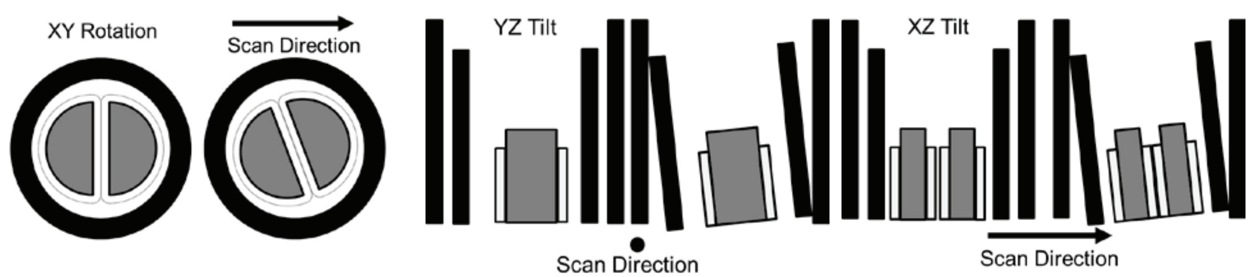
VIC-3D® solves for the necessary fields (electric and magnetic) by calculating the anomalous fields in the coil, cores and shields if present. A regular mesh is used when ferrite cores and shields are present with the remainder of the computational domain being solved with Green's Functions. The probe mesh for these simulations was 32x32x32 (x, y, and z respectively) while the defect mesh was 32x2x16. The rationale for the very fine probe mesh will be discussed in the next section. The mesh resolution chosen for the defect is to ensure the volume elements do not become skewed in one dimension. With the current resolution, all sides of the volume elements are roughly the same length. The Ti-6Al-4V specimen conductivity was set to an assumed value of 0.58 MS/m [11] and the relative permeability (μ_r) of the ferrite cores and coils was set to 3000.

Model Construction

The general construction of the probe model is similar to those constructed in past effort. The 4-coil method of construction [6] is used to reduce the post processing of the simulated results. In all simulations, dimensional differences in the cores and coils have been included to increase the realism of the probe model. However, due to the more complex nature of the problem being simulated, extra care was taken to ensure the mesh created is consistent as the angles vary and does not introduce extraneous error into the solution. A bounding box was created, with the properties of air, to surround the entirety of the probe (cores, coils, and shield). The box was set normal to the specimen surface and parallel to the scan direction. This ensures that no matter what variations occur with the core and coils the mesh, which is controlled by the largest object in the field, remains constant. The very fine mesh, particularly in the Z direction, is necessary to ensure sufficient resolution when the cores are angled. As the probe is angled small portions of the core will begin to move from one voxel to another. If there is not sufficient resolution in the Z direction these small core components will not be represented correctly and thus the field created by them will be incorrect. This creates noise and error in the final solution that needs to be avoided

Angular Variations

As mentioned previously, past model validation efforts [7-8] have incorporated orientation variations with considerable success. However, these previous studies only included variations at one prescribed angle based on the dimensions of the probe. To perform a sensitivity study more information is needed. Moreover, these previous studies had variations in only one major plane. This study will investigate angular variation in all three major planes with a range of values for the angle. The range of values will be from -10^{o} to 10^{o} in steps of 1^{o}. This range encompasses the extreme values seen for various types of differential probes. However, for the commercial pencil probe design modeled in this study there are no metrics for the possible extent of variations. The planes that are going to be investigated are rotations around the three principal axes of the probe. Figure 2 shows diagrams of the three cases and their orientation compared to the scan direction. Figure 2c shows the orientation that was modeled in previous validation studies. The scan direction for the YZ tilt, Figure 2b, is in and out of the page and contrary to the position of the dot in the image would be centered under the probe. In all cases, a level of symmetry should be expected in the results based on the variation angles, but there will not be perfect symmetry due to the dimensional differences that have been included in the models.



(a) (b) (c)

FIGURE 2. Images of the variation in orientation simulated in this effort, a) a rotation about the Z axis of the probe, b) a rotation around the X axis of the probe, c) a rotation around the Y axis of the probe

RESULTS AND DISCUSSION

The results will be separated based on the plane in which the variation occurs. Both the change in resistance and change in reactance data will be shown in separate plots. In all cases, the extreme results (±10 degree data) will be shown with the 0-degree or nominal case. For the XZ tilt case, there will be additional data and analysis presented due to the large response change. In this case, the sensitivity of the response with respect to the angle will be calculated with a simple finite difference scheme.

XY Plane Rotation

Figures 3a and 3b show the results when the probe is rotated in the XY plane. Neither component shows any considerable affect from the variation in terms of magnitude or shape. There is an interesting artifact in the response in that the expected symmetry is not present. This is more evident in Figure 3b where the 10-degree data set is shifted positively from both the 0 and -10 degree data. In contrast, the 0 and -10 degree data sets are nearly identical in both magnitude and shape.

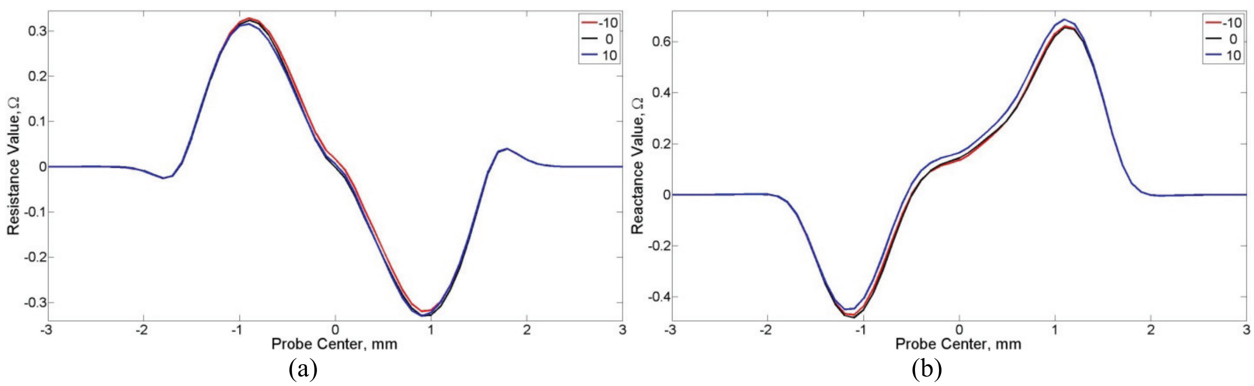
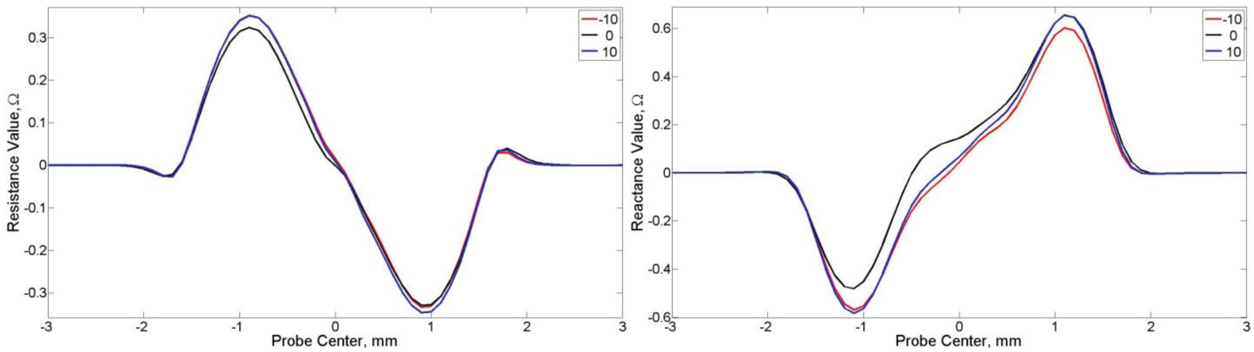


FIGURE 3. a) Change in resistance and b) change in reactance for 3 cases of the probe rotation in the XY plane

YZ Plane Tilt

The other two orientations produce higher levels of variation due to the more drastic alterations of the probe incidence field. Figure 4a shows small but noticeable changes in both amplitude and shape for the resistance data. However, Figure 4b shows a large shape response change compared to the nominal case. The knowledge that variations in this plane lead to noticeable shape changed could be used to aid the agreement seen in past validation efforts. As with the XY plane, asymmetry can also be seen in the YZ plane, most noticeably at the major peaks in Figure 4b. The negative major peaks has both the -10 and 10 degree results as having roughly the same value and being shifted negatively from the 0 degree case. Conversely, with the positive major peak, the 0 and 10 degree cases have nearly identical values and the -10 degree case is shifted. The resistance data shows a similar trend to the XY plane reactance data. The 10-degree data set shows noticeably variation compared with the 0-degree case. However, the -10 degree case is nearly identical to the 0-degree case. These asymmetric artifacts are interesting when the coil behavior at the extreme values is considered. One would expect the field from the -10 degree case to be similar to the field for the 10-degree case, and thus produce more symmetric results.



(a) (b)

FIGURE 4. a) Change in resistance and b) change in reactance for 3 cases of the probe rotation in the YZ plane

XZ Plane Tilt

Based on the results of past validation efforts and the results from the other orientations presented in this paper the response change produced by variations in the XZ plane are going to be the most dramatic. Figure 5a and 5b compare the extreme and nominal cases. Clearly, there is a much larger change in both components in both shape and amplitude. The shape change manifests itself mainly in the change in reactance data, as with previous orientations. Both the shape and magnitude changes come from having one coil closer to the surface of the specimen. This leads to the field of one coil overwhelming the other when the differential signal is taken. Figure 5c and 5d show all the data for the XZ plane tilt. In looking between Figure 5a and 5c there are some noticeable discrepancies that arise. The most concerning being that certain angles below the 10-degree case actually have higher amplitudes than the extreme case. This causes a large gap to form in the overall data spread. This numerical noise could be the result of errors in the probe mesh. While there are no large gaps in the reactance data, there are still areas of concern. There are areas where the values from different angles are nearly identical, which could be the result of errors in the probe discretization due to the small changes to core elements from small angle changes. This can be seen in the negative peaks for the positive angles. In addition, there is a pronounced difference in the spacing at the two extremes of the data. The line displayed in Figure 5c and 5d is the location for a slice of data that will be used for the sensitivity analysis. The slice is aligned with the maximum value of the nominal case for each component.

Sensitivity Analysis

Figure 6 shows the data associated with the slice of data from Figure 5c and 5d. It is with this data that the sensitivity analysis will be performed. The red line in each plot is a 3rd order polynomial fit to the raw data. The resistance data in Figure 6a is very scattered and discontinuous compared to the reactance data. This is the result of numerical noise that was hinted at in the previous section coupled with the smaller magnitude of data for this component. Figure 6a shows the troubling result discussed above where the data for angles 3-9 degrees is higher in magnitude than the 10-degree case. While not as bad as the resistance data there is still numerical noise present in the reactance data. The reactance data is not centered on the line, for a majority of the data points. In addition, there is a very interesting feature to the reactance data. There is a positive and negative minor humps on either side of the 0-degree data marker. This could result in some very interesting results when the sensitivity analysis is performed. Because of the amount of numerical noise in the raw data, the fit line will be used for the sensitivity analysis. For this study, the sensitivity with respect to the angle will be computed using a simple finite difference scheme (3).

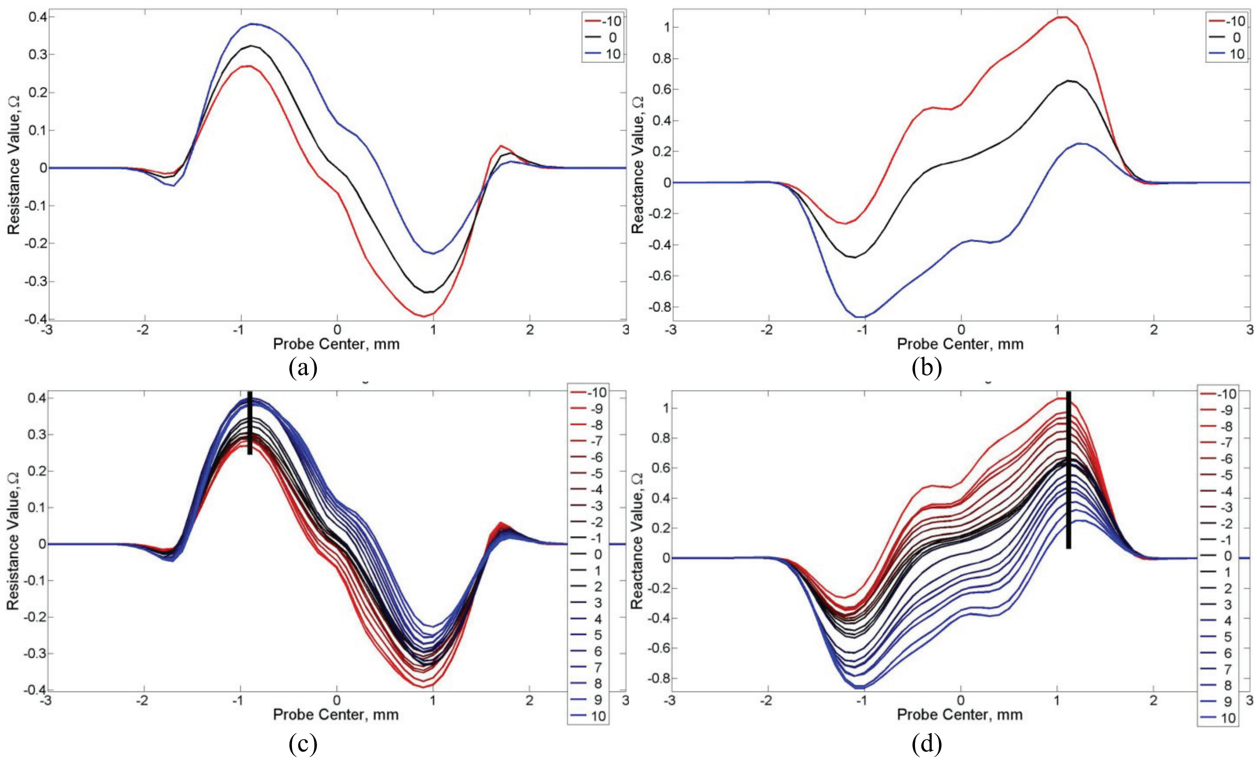
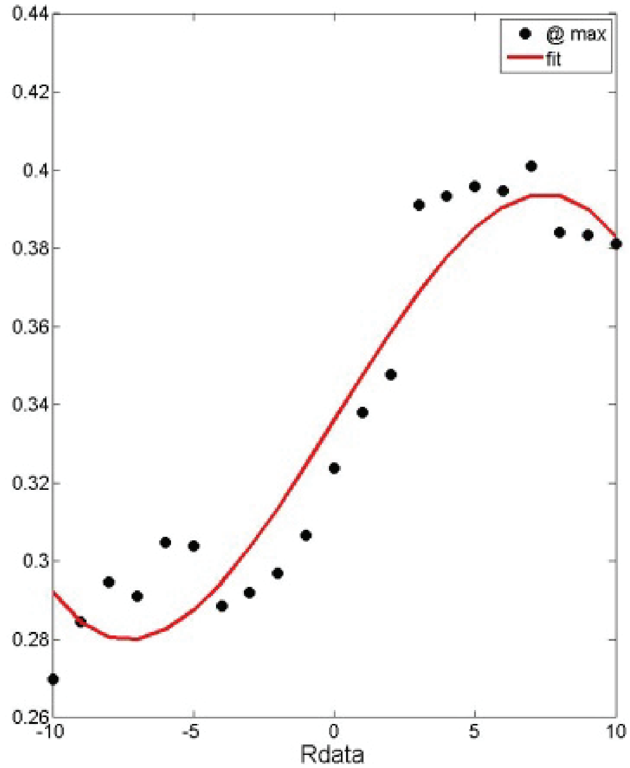


FIGURE 5. a) Change in resistance and b) change in reactance for the extreme probe rotation cases for the XZ probe tilt. c) Change in resistance and d) change in reactance for all the data for the XZ probe tilt.

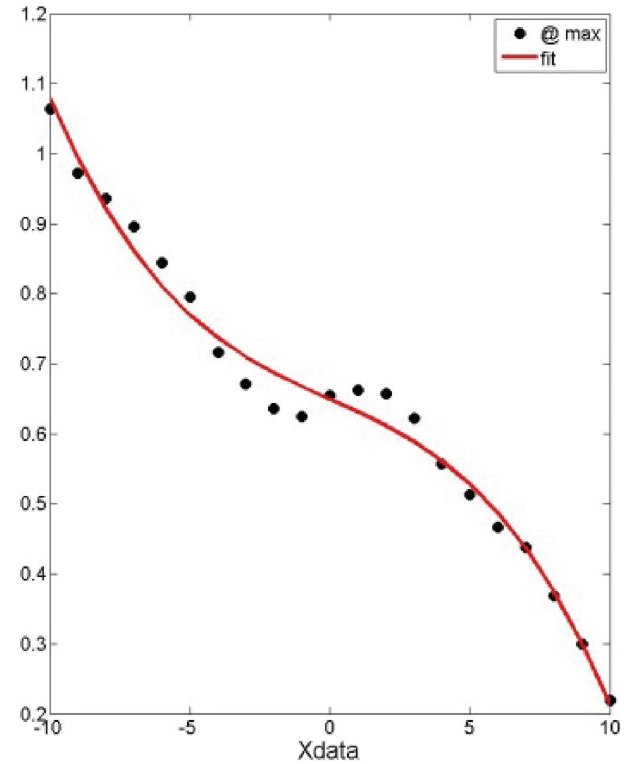
$$\frac{d}{d\theta} = \frac{X_{\theta_i} - X_{\theta_{i+1}}}{\theta_i - \theta_{i+1}} \tag{3}$$

$$PC = \left(\frac{\left|X_{\theta_i} - X_{\theta_0}\right|}{\left|X_{\theta_0}\right|}\right) * 100 \tag{4}$$

Figure 7 shows the sensitivity results based on (3). The reactance data shows a great deal more change compared to the resistance. If we focus on the reactance data, some trends can be seen. The change in the derivative values between ±4 degrees is roughly 0.01, while the change outside this range is nearly 6 times greater. This indicates there may be a range of angular values where the probe response may be less sensitive to the angular variation. In looking back at Figure 6b this range corresponds to the minor humps seen in the reactance data. Figure 8 shows the percent change from the 0-degree case for each angle. The percent change was calculated using (4). A similar trend can be seen with the percent change in the reactance data. In the range between ±4 degrees, the percent change is roughly 10%. However, outside of this region the change jumps from 10 to nearly 70 percent in 6 degrees. This range again corresponds with the range seen in Figure 6b and shows that there are potential areas that could be less sensitive to the angular variation.



(a)



(b)

FIGURE 6. a) Resistance and b) Reactance data as a function of variation angle at one scan point with a 3rd order polynomial fit

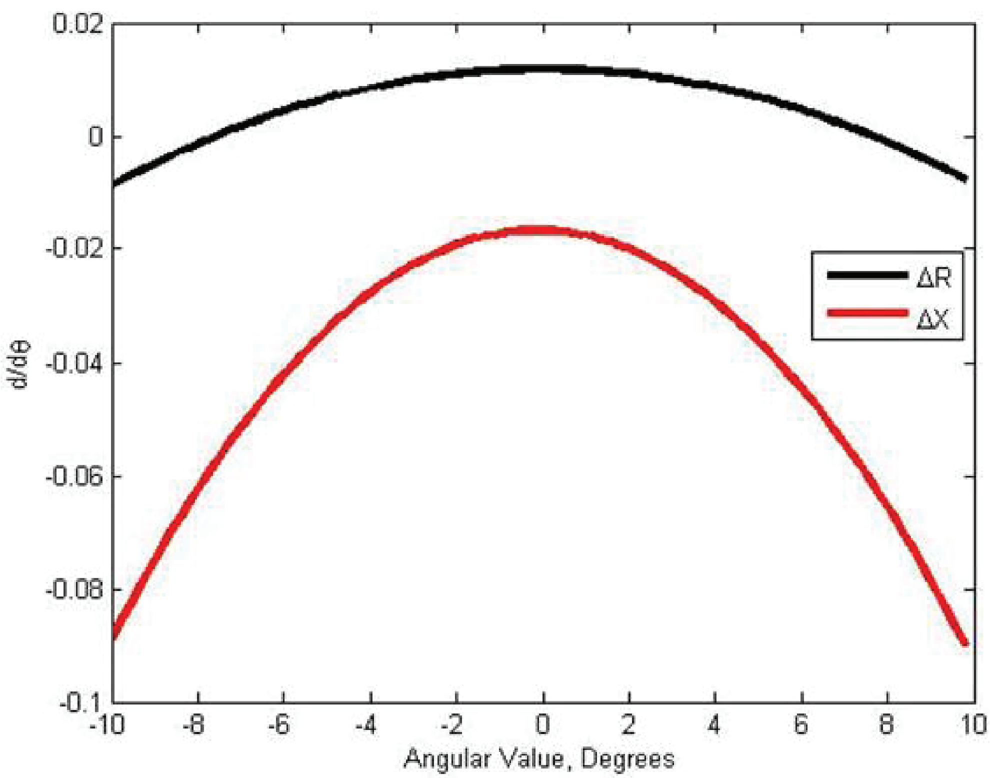


FIGURE 7. Plot of the derivative values for the fit line for both the resistance and reactance data.

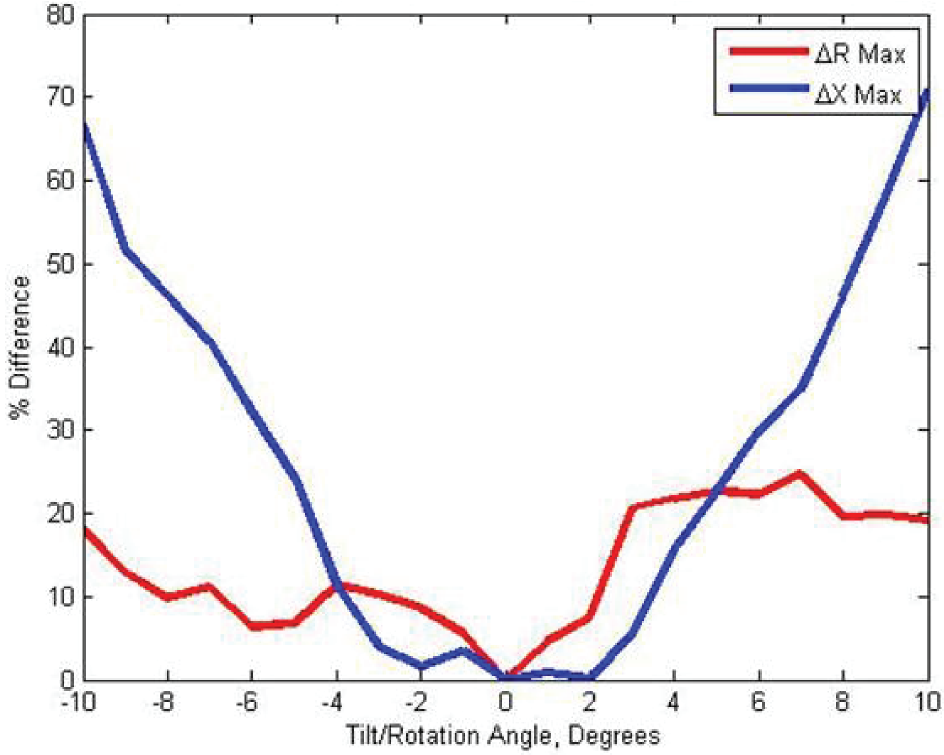


FIGURE 8. Plot of the percent change from the 0-degree case for each component of the data with respect to variation angle.

SUMMARY

From the above results, there are clearly certain orientations in which angular variations will produce drastic changes in the probe response, while others produce only minor changes. The XY plane rotation produced only minor shifts in the probe response, and mainly in the reactance component. The YZ plane tilt did produce more substantial response changes including noticeable shape changes in both components. These shape changes could be useful in improving the validation results for data presented in the past for other scan directions. The XZ plane tilt produced the most dramatic changes in probe response in terms of both shape and amplitude. The results presented here do show numerical noise which needs to be further investigated. Regardless of the noise, there are trends that can be seen in the data. In looking at the XZ plane data there are regions in the overall change where the variation angle produces little effect on the probe response. The data analysis performed in the study was rather simple, but for a first step it provided necessary insight into the problem. The results from this study not only provide insight into probe characterization they can be applied to past validation studies.

Concerning the noise issues discussed in previous sections. The volume element method [9-10] used to simulate the split-D differential probe applies a 3D grid of volume elements to mesh the current sources and ferrite cores of the probe. When certain levels of tilt are applied, the active elements of the probe grid, fixed to the Cartesian coordinate system, will change depending on the degree of tilt, in particular on the side of the probe nearest to the specimen (see Figure 9). This numerical approach will thus distribute the current source for the D-shaped coils through the sides of the entire grid element. It appears that jumps in the response, the numerical noise, are associated with step changes in active mesh elements in how the tilted probe is meshed. To avoid these jumps in the solution, more mesh resolution is clearly needed with the core/coil portion of the probe tilted toward the surface, as shown in Fig. 9(c), to ensure convergence of the numerical solution. However, with increasing mesh resolution can produce significantly greater solution time. To further address this numerical error, a tedious but viable approach would be to simulate the probe at a variety of angles of tilt, and then use a polynomial fit through the data to interpolate between points with the highest numerical error.

Additional work is needed to verify the numerical solution for tilted probe. First, benchmark studies with experiments under well controlled tilt conditions are needed to verify the numerical solutions. In these studies,

addressing variation in magnitude of the signal is only one aspect of verifying model accuracy. The biggest change with tilt angle appears to be associated with the shape change in the response, where one side of the probe response is much more sensitive (since it is closer) while the other side that is less so. For inversion, these shape changes are critical for inverting the probe state and thus enabling accurate flaw sizing.

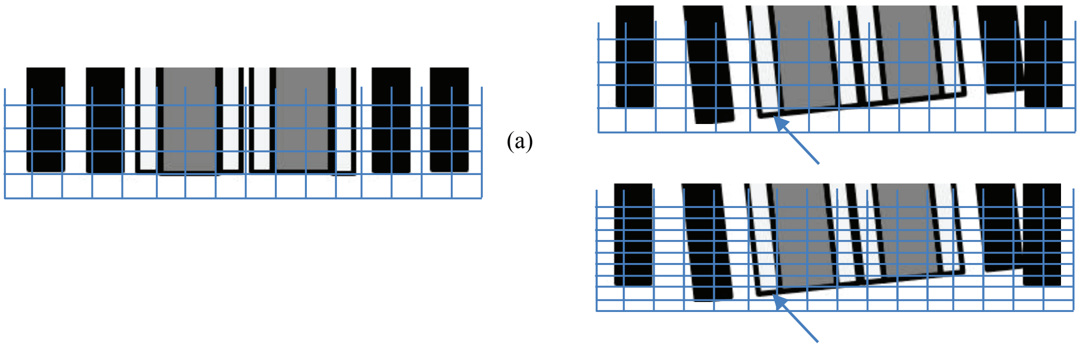


FIGURE 9. Diagram showing a near section of the volume element discretization for (a) normal and (b) YZ plane tilted probes. More discretization in the z-direction is likely necessary for titled probes (c) to smooth out step changes as the coil and core elements are positioned into volume elements nearer to the test part surface (see arrow).

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REFERENCES

1. A. Schumm and N. Nakagawa, "Code Validation for Eddy Current Modeling Tube Inspections with Reflection Differential Probes", *in Review of Progress in Quantitative Nondestructive Evaluation*, eds. D.O. Thompson and D.E. Chimenti, (American Institute of Physics 760, Melville, NY), **24**, 509-515 (2005).
2. N. Nakagawa, T.A. Khan, J. Gray, "Eddy Current Probe Characterization for Model Input Validation," in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D.O. Thompson and D.E. Chimenti, (American Institute of Physics 590, Melville, NY), **24**, 473-480 (2005).
3. N. Nakagawa, M. Yang, B.F. Larson, E.M. Madison, and D. Raulerson, "Study of the effects of EDM Notch Width on Eddy Current Signal Response," *in Review of Progress in Quantitative Nondestructive Evaluation*, eds. D.O. Thompson and D.E. Chimenti, (American Institute of Physics 1096, Melville, NY), **28**, 287-294 (2009).
4. O. Moreau, F. Buvat, C. Gilles-Pascaud and C. Reboud, *An Approach for Validating Eddy Current Simulation Codes,* Proceedings of the Seventh International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, June 2010.
5. R.D. Mooers, J.S. Knopp and M.P. Blodgett, "Model Based Studies of the Split D Differential Eddy Current Probe," in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D.O. Thompson and D.E. Chimenti, (American Institute of Physics 1430, Melville, NY), **31**, 373-380 (2012).
6. R.D. Mooers, J.S. Knopp, J.C. Aldrin, and S. Sathish, "Split D Differential Probe Model Validation Using and Impedance Analyzer," in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D.O. Thompson and D.E. Chimenti, (American Institute of Physics 1581, Melville, NY) **33**, 1511-1518 (2013).
7. R.D. Mooers, J.C. Aldrin, and J.S. Knopp, "Realistic split D differential probe model validation," in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D. E. Chimenti and L. J. Bond, (American Institute of Physics 1650, Melville, NY) **34**, 385-394, (2015).
8. R.D. Mooers, J.C. Aldrin, and J.S. Knopp, "Model the Effects of Core/Coil Size and Defect Length on Eddy Current Response," in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D. E. Chimenti and L. J. Bond, American Institute of Physics, 1650, Melville, NY) **34**, 395-404 (2015).
9. R.K Murphy, H.A. Sabbagh, J. Chan and E. H Sabbagh, "A Volume Integral Code For Electromagnetic Nondestructive Evaluation," in *Proceedings of the 13th Annual Review of Progress in Applied Computational Electromagnetics*, March 1997
10. Sabbagh, H. A., Murphy, R. K., Sabbagh, E. H., Aldrin, J. C., and Knopp, J. S., *Computational Electromagnetics and Model-Based Inversion - A Modern Paradigm for Eddy-Current Nondestructive Evaluation*, Springer, (2013).
11. http://www.ndt-ed.org/GeneralResources/MaterialProperties/ET/Conductivity_Ti.pdf.